A Robust Higher-Order Shimming Application

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Introduction:

Many advanced applications such as spectroscopy, fast imaging sequences, or fat/water imaging techniques have stringent requirements on the homogeneity of the magnetic field. As such, many scanners currently are equipped with 2nd order resistive shim coils along with their gradient coils for improving magnetic field uniformity during clinical imaging. Significant development has focused on developing fast field-mapping techniques coupled with automated routines for calculating what current to apply to the shim coils. The choice of technique for field map acquisition, like any imaging acquisition, has trade-offs that require careful consideration. Fast imaging techniques such as EPI or spiral can be acquired very quickly, but are inherently sensitive to the same B_0 inhomogeneities that are being measured, resulting in geometric distortion and/or signal loss in the resulting map. Additionally, these fast imaging techniques require fat saturation, which limit their utility for applications such as breast or musculoskeletal imaging.

Rather than focus on a fast shimming technique, we have chosen instead to design a robust shimming application that will provide improved shim for a wider range of imaging or spectroscopic applications. This new application consists of 1) using a 2D fast gradient echo (2D FGRE) imaging sequence with echo shift (ΔTE) chosen such that fat and water are in-phase for a given field strength, 2) multi-channel image reconstruction, 3) on-the-fly generation of corresponding reference field maps measured from each of the shim coils on a system-by-system basis, and 4) 3D phase unwrapping within a user selected ROI.

Methods:

In vivo images were acquired on a GE 3T scanner using both the existing product high order shimming tool (spiral field map acquisition) as well as the 2D FGRE field mapping sequence. Image acquisitions were matched for resolution (128x128x64) and field of view, each consisting of a 48x48cm axial FOV over a 37cm volume extending from the shoulders down through the abdomen. SNR measurements were calculated over regions of interest placed over the shoulders, superior and inferior regions of the liver, and the lungs. 3D phase unwrapping was applied to the 2D FGRE images over the entire volume.

To approximate the field generated by each of the 1st and 2nd order shim coils, the product LVShim tool was used to measure and fit the field using a spherical harmonic expansion up to 12th order in the zonal harmonics and up to 3rd order in the tesseral harmonics. This calibration procedure would be performed once per system installation. The coefficients are stored on the system to generate on-the-fly reference maps of the shim fields that correspond to the geometric prescription of the 2D FGRE field mapping sequence. Existing software to perform a least squares fit of the in vivo field maps to the reference maps was used [1]. To validate the accuracy of this technique, the on-the-fly reference maps were correlated against existing spiral reference maps for 28x28x21cm and 48x48x37cm image volumes.

Results:

The in vivo images are shown in Fig. 1. The spiral images demonstrate the lack of fat signal and signal drop out in regions of large field inhomogeneity. The 2D FGRE field mapping images maintain signal in regions of fat and field inhomogeneity, enabling high-order shimming over these regions. The yellow circles indicate the ROIs used for signal measurements. The table provides the SNR measurements. It should be noted that regions of low SNR are excluded from the least squares fit. Fig. 2 provides an example of the robustness of the 3D phase-unwrapping algorithm over a large FOV with multiple phase-wraps.

On-the-fly reference maps were highly correlated with the corresponding spiral reference maps, with the lowest correlation-coefficient r = 0.953 for the small FOV occurring with the Z^2 reference field, and r = 0.941 for the large FOV occurring for the X^2-Y^2 reference field.

Discussion:

Fast field-mapping techniques such as spiral or EPI have provided tremendous benefit for many applications. However, in addition to their sensitivity to B_0 inhomogeneities, these techniques typically require that reference maps be acquired to exactly match the in vivo maps such that gross geometric distortion due to static field inhomogeneities can be accounted for. Generation of quality reference maps for each desired in vivo geometry can be very time consuming, and this also limits flexibility for the user.

Geometric distortion for 2D FGRE field mapping is orders of magnitude smaller than spiral or EPI, allowing the use of reference maps generated on-the-fly from a single set of coefficients measured at installation. On-the-fly reference maps enable the user to prescribe various geometries at arbitrary image resolutions, allowing small off-center FOVs conducive to musculoskeletal imaging, or higher resolution field maps to avoid intra-voxel dephasing in regions of severe susceptibility. However, field-mapping is restricted to the axial plane to minimize distortion due to gradient non-linearity. The need for regularization and/or constraining of the least squares fitting routine also remains to be investigated for small, off-center FOV applications [1,2].

Multi-channel support improves the utility of the shimming tool, providing higher SNR and also providing compatibility with phased-array transmit-receive coils or systems that lack body coils. Squared magnitude data is used to weight the multi-channel complex phase data, similar to the processing for multi-channel phase contrast imaging.

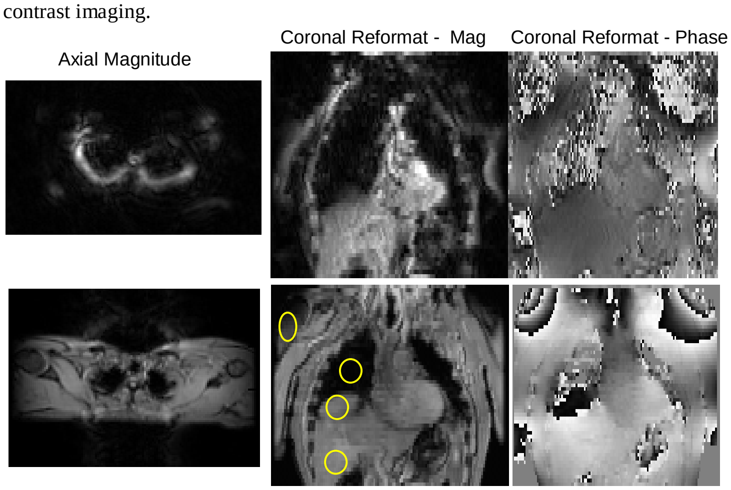

Fig. 1: Top row shows spiral field mapping image quality through chest, shoulders and abdomen. Bottom row shows corresponding image planes acquired with 2D FGRE field mapping.

Table: SNR measurements

ROI	Spiral	FGRE
Shoulder	2.2	51.8
Sup. Liver	11.3	139.0
Inf. Liver	64.4	168.2
Lung	6.1	11.9

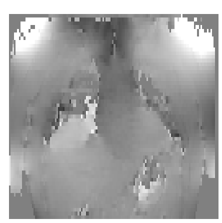

Fig. 2: 3D phase unwrapping applied to 2D FGRE dataset.

Conclusion:

A robust higher-order shimming application is introduced using a 2D FGRE imaging sequence. This technique enables shimming in regions of high-susceptibility or areas of high fat content. On-the-fly generation of reference maps provides flexibility in prescribing the geometric location of the field-mapping acquisition. 3D phase unwrapping and multi-channel support further enhance the application.

References:

[1] Kim et al. MRM 48:715-722, 2002.
[2] Kim et al. ISMRM 11 :2165, 2004.